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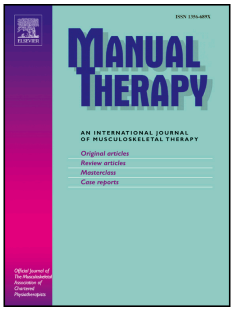

Interactive cervical motion kinematics: Sensitivity, specificity and clinically significant values for identifying kinematic impairments in patients with chronic neck pain

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The diagnostic value of cervical kinematics in chronic neck pain

Title page

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Interactive cervical motion kinematics: sensitivity, specificity and clinically significant values for identifying kinematic impairments in patients with chronic neck pain.

Abstract

Chronic neck pain has been consistently shown to be associated with impaired kinematic control including reduced range, velocity and smoothness of cervical motion, that seem relevant to daily function as in quick neck motion in response to surrounding stimuli. The objectives of this study were: to compare interactive cervical kinematics in patients with neck pain and controls; to explore the new measures of cervical motion accuracy; and to find the sensitivity, specificity, and optimal cutoff values for defining impaired kinematics in those with neck pain.

In this cross-section study, 33 patients with chronic neck pain and 22 asymptomatic controls were assessed for their cervical kinematic control using interactive virtual reality hardware and customized software utilizing a head mounted display with built-in head tracking. Outcome measures included peak and mean velocity, smoothness (NVP), symmetry (TTPP), and accuracy of cervical motion.

Results demonstrated significant and strong effect-size differences in peak and mean velocities, NVP and TTPP in all directions excluding TTPP in left rotation, and good effect-size group differences in 5/8 accuracy measures.

Regression results emphasized the high clinical value of neck motion velocity, with very high sensitivity and specificity (85%-100%), followed by motion smoothness, symmetry and accuracy. These finding suggest cervical kinematics should be evaluated clinically, and screened by the provided cut off values for identification of relevant impairments in those with neck pain.

Such identification of presence or absence of kinematic impairments may direct treatment strategies and additional evaluation when needed.

Keywords: Neck pain, kinematics, virtual reality, sensitivity

Interactive cervical motion kinematics: sensitivity, specificity and clinically significant values for identifying kinematic impairments in patients with chronic neck pain.

Introduction

Neck pain is a common musculoskeletal disorder with an annual prevalence of 30% to 50% in western populations,(Hogg-Johnson et al. , 2008, Holm et al. , 2008) and thus serious consequences for health care systems and society.(Lidgren, 2008) Clinical assessment of disability and impairment of function is currently the accepted approach for evaluation and treatment of patients complaining of neck pain.(Childs et al. , 2008)

The existing literature shows neck pain to be associated with various impairments such as restricted range of motion (ROM),(Nordin et al. , 2008) increased repositioning error,(Heikkila et al. , 1998, Treleaven et al. , 2003) compromised isometric strength,(Dvir and Prushansky, 2008) and reduced endurance of the cervical muscles.(Jull et al. , 2008) However, much of our daily neck function is dynamic in response to multiple visual, auditory, or scent stimuli, and therefore emerging research is exploring the dynamic characteristics of neck motion in patients with neck pain. Theoretically, normal voluntary motion should have a near symmetrical bell-shaped velocity profile with a single velocity peak and equal acceleration and deceleration phases (Vikne et al. , 2013). Studies have consistently showed that velocity and smoothness of cervical motion is reduced in patients with chronic neck pain (Sjölander et al. , 2008, Roijezon et al. , 2010, Sarig Bahat et al. , 2010, Tsang et al. , 2013) and motion accuracy is impaired when compared to asymptomatic individuals (Kristjansson and Oddsdottir, 2010, Roijezonet al., 2010, Sarig Bahatet al., 2010, Woodhouse et al. , 2010b).

Our previous kinematic research explored the effect of neck pain on the dynamic characteristics of cervical motion using a virtual reality system to simulate functional neck motion.(Sarig Bahat et al. , 2009, Sarig Bahatet al., 2010, Sarig-Bahat, 2011) The kinematic measures that were characteristic of patients included decreased ROM, mean and peak velocity, and altered smoothness of cervical motion, in flexion, extension and rotation. Time to peak velocity, which represents the symmetry of motion i.e. acceleration-deceleration ratio, was not found to be different between patients and controls, although others have shown less symmetry in the velocity profile of neck pain patients(Roijezonet al., 2010).

Previously we reported on the sensitivity and specificity of this methodology to evaluate cervical ROM impairment. Findings demonstrated 88% sensitivity for flexion/extension and 76% for rotation ROM(Sarig-Bahat et al. , 2010). Given the functional relevance of measures such as velocity of head motion, it would seem important to now consider the clinical value of these other kinematic measures to identify relevant impairments using this system. Further there is potential value to expand our investigation of kinematic impairments using this device and examine additional measures of motion accuracy in patients with neck pain compared to asymptomatic controls.

Investigation of the sensitivity, specificity and clinically significant values for identifying kinematic impairments in patients with chronic neck pain is an important step to assist future research on the effect of training of such impairments in the management of neck pain. Thus the objectives of this study were: to compare cervical kinematic characteristics during interactive motion in patients with neck pain and controls, including mean and peak velocity, smoothness and symmetry of cervical velocity profile; to explore the new outcome measure of cervical motion accuracy which has not been evaluated before in this interactive fashion; and to find the sensitivity and specificity of each of the differentiative kinematic measures in order to obtain the optimal cutoff values for defining impaired kinematics in those with neck pain. This will ultimately assist in determining the need for management directed towards these impairments.

Materials and Methods

Participants

The research population included patients presenting with chronic neck pain, and control participants with no physical complaints in the neck region. Participants were recruited at the University of Queensland and at the University of Haifa as a sample of convenience. Inclusion criteria for the patient group were complaints of neck pain for 3 months or more, with or without referral to the upper limb. Exclusion criteria for the patient group included limited neck range of motion less than 40 degrees in each direction, neurological disorders including positive neurological signs or imaging evidence indicating of nerve root/spinal cord compression; systemic disorders such as rheumatic syndromes, diffuse connective tissue diseases, metabolic/endocrine diseases, neoplasm, fractures or dislocations; and spinal surgery. Only individuals who reported no physical symptoms, no neurological, visual (unless corrected), or vestibular disorders were recruited to the control group. The study was approved by the Institutional Review Boards of the University of Queensland and the University of Haifa.

VR assessment system

We used a new customized VR system to evaluate cervical kinematics with a simple interactive scenario monitored via motion tracking. This new system included new hardware and more advanced software following similar principles of the previously developed prototype (Sarig Bahatet al., 2009). The hardware consisted of a head mounted display with a built in motion tracker (Wrap™ 1200VR by Vuzix, New York, www.vuzix.com), equipped with gyroscopes, accelerometers and magnetometers. Sampling rate was 30Hz and display resolution was 1280x720.

Customized software was used in this study, consisting of an interactive three-dimensional virtual environment that was developed using the Unity-pro software, version 3.5 (Unity Technologies, San Francisco). The Vuzix Software development kit was also used. Dynamic motion tracking data were analyzed by the developed software in real-time. Two interactive modules, the velocity and accuracy modules were used in this study (Figures 1,2). During both VR modules, the virtual pilot flying the red airplane is controlled by the patient's head motion and interacts with targets appearing from four directions (flexion, extension, right rotation, left rotation). In the velocity module, the participant had initially to stabilize the virtual pilot inside a circle, which reflected mid-position. As soon as this mid-position was stable for three seconds, the game was activated and a target appeared (Figure 1). Then the participant was instructed to hit the target as fast as possible, before it disappeared after 7 seconds, and had to return to mid-position each time. Target's life time was visualized using a green circle around the target that diminishes gradually and functions as a timer (see Figure 1). This feature aims to motivate the participant to move quickly towards the target before it disappears. The target was positioned at 40 degrees of range. The velocity module included two warm-up trials, followed by 16 assessment trials, four in each direction. Directions of the targets were randomly ordered. A full kinematic report for each patient was generated. The accuracy module consisted of an interactive task where the participant was required to keep the pilot's head on the virtual moving target (Figure 2). The presented target moved in a constant velocity of 10 degrees/sec in four movement directions, including 8 trials, 2 in each direction.

Subjective measures

Participants with neck pain completed the following questionnaires, reflecting different aspects of their disorder:

Visual Analogue Scale (VAS)(Langley and Sheppeard, 1985, Breivik et al. , 2000, Wainner et al. , 2003): Patients were requested to indicate on a 100mm line the point that best represented their level of neck pain and dizziness.

Neck Disability Index (NDI) (Vernon, 2008) is a self-rated instrument assessing disability due to neck pain that consists of 10 items related to daily living activities. Each item was rated 0-5, and the sum was represented in percentage.

Tampa Scale of Kinesiophobia (TSK)(Sullivan et al. , 2002) is a 17-item questionnaire used to assess fear of movement or re-injury, in which patients are asked to rate their level of agreement with each item on a four-point scale (1-4). Scores greater than 37/68 indicate a high degree of kinesiophobia (Vlaeyen et al. , 1995).

Kinematic outcome measures

The following are the definitions of the cervical motion kinematics outcomes:

1. Peak velocity (Vpeak, °/sec) was collected from 16 trials, four from each direction. The overall Vpeak result was calculated as the mean of the three maximal results achieved from each direction.
2. Mean velocity (Vmean, °/sec) was calculated as the mean angular velocity of three maximal results achieved from each direction.

Peak and mean velocity measure the angular velocity of the head. Peak velocity is important to give an indication of the maximum velocity of head motion reached, and mean velocity gives an indication of the overall speed of the head motion including the acceleration and deceleration phases. Functionally, quick motion of the head is required in daily life in response to various stimulations such as when driving, when responding to a loud noise, call, touch or even when tracing a scent.(Takasaki et al. , 2013, Tsanget al., 2013)

3. Number of velocity peaks (NVP) refers to the number of velocity peaks from motion initiation to target hit, indicating motion smoothness. Normal smooth motion should optimally have only one peak velocity. NVP was defined by counting the number of times that the acceleration curve changed sign, i.e., crossed the zero line. NVP thus represents the smoothness of motion, which is considered to be important for efficient and normal movement patterns. Less smooth motion and more velocity peaks is thought to reflect irregular motion and abnormal movement control.(LoPresti et al. , 2003, Vikneet al., 2013)

4. Time to peak velocity percentage (TTPP) was defined as the time from motion initiation to the peak velocity moment, as a percentage of total movement time. Relative time to peak velocity has been studied in human motion, and is considered optimal when presenting a symmetric bell-shape velocity profile with a 1:1 acceleration-deceleration ratio, or in other words a 50% TTPP (Nelson, 1983, Hogan, 1984). Previous findings relating to TTPP in symptomatic neck motion were inconsistent which emphasised the need for further investigation (Roijezonet al., 2010, Sarig Bahat et al. , 2014b). TTPP thus reflects the symmetry of the acceleration and deceleration phases of the velocity profile.

5. Head movement accuracy was collected during the accuracy module (Figure 2), where the participant was required to keep the pilot's head on the virtual moving target. Motion accuracy was defined as the difference between target position and participant's head location in degrees. This difference (target-player's position) in the pitch# and the yaw# plane were derived from the sum of the trials in each plane. Head motion accuracy has been investigated by others previously using other methods and was shown to be impaired

in patients with neck pain (Kristjansson and Oddsdottir, 2010, Woodhouse et al. , 2010a), this study investigated this measure for the first time in an interactive fashion.

Measures 1-4 were collected during the velocity module (Figure 1) and measure 5 was obtained during the accuracy module (Figure 2).

Insert Figures 1-2 here

Pitch stands for angular motion in the sagittal plane, which in the cervical spine produces flexion-extension, yaw –for motion in the horizontal plane that produces right and left rotation.

Kinematic measures were analyzed from the tracking data. For the velocity module, we defined each trial period as the time from target appearance to target hit. Data were low pass filtered (Butterworth, 6 Hz, order 4), and an angular velocity profile was computed for each trial from angular rotations (i.e., roll, pitch, and yaw). We calculated mean values of the kinematic outcome measures for each of the four directions (flexion, extension, right rotation, and left rotation). Motion initiation was determined as the point in time when 5% of peak velocity was obtained.

Procedure

The experimental session commenced with an interview regarding possible exclusion criteria, as well as completion of the questionnaires by the patients. The assessors were experienced physiotherapists. Cervical VR assessments were carried out in the sitting position, with the trunk secured to a chair by a seatbelt and feet resting on the ground. A short warm-up and introductory explanation of the virtual game was conducted prior to the assessment. Time of the VR assessment was approximately 10 minutes (5min for velocity assessment, and 4-5 minutes for accuracy). Output data files were generated automatically by the software and were exported to excel datasheets, which were available for analysis following completion of data collection.

Statistical Analysis

We calculated the mean value of the three best trials for each kinematic measure in each motion direction (F, E, RR, and LR). We assessed differences between the two groups (patient vs. control) using an independent variability t-test, after assuring normal distribution of data. Logistic regression and ROC (Receiver Operating Characteristic) curves analyses were performed separately for each kinematic measure as a predictor of impairment in each patient as compared with normative data from the asymptomatic individuals. ROC Area Under Curve, optimal test cut offs, sensitivity, specificity and odds ratios were also determined, with their Clopper-Pearson confidence limits.

Effect size was analyzed for each measure using Cohen's d.

Significance was determined at $p<0.05$. SAS® software (Statistical Analysis Software, www.sas.com) was used.

Results

Kinematic assessments were performed on 22 control participants (8 females, 14 males, mean age 33±6.78), and 33 patients (20 females, 13 males, mean age 37.56±9.95). There were no significant differences in age or gender between the patient and control groups ($p>0.05$). Table 1 presents the characteristics of the patient group including symptoms duration, intensity (VAS), and disability (NDI). Almost half of the patients were regularly taking medication (15 on, 18 off) however preliminary analysis revealed no significant differences between those taking and not taking medication for pain intensity (VAS), disability (NDI), fear of motion (TSK), and any of the cervical motion performance (kinematic measures).

Table1. Characteristics of patient group (N=33)

Patient characteristics	Mean	SD	Range

Neck pain duration (months)	93.03	104.49	5-360
Pain intensity (VAS /100mm)	36.42	17.24	8.64-69.77
Dizziness intensity (VAS /100mm)	12.71	22.42	0-90
NDI%	23.5	12.7	6-64
TAMPA scale of kinesiophobia	32.64	6.85	21-47
Patient characteristics			
Aetiology: Whiplash associated disorders*; idiopathic neck pain	12	21	
Symptoms' distribution: central/bilateral; unilateral (R,L)	18	15 (9,6)	
Regular medication intake: yes; no	15	18	
Medication type: pain control; systemic; anti-depressants	7	8	5

SD- standard deviation; VAS- visual analogue scale; R- right; L- left
* All 12 patients with whiplash associated disorders were classified as WAD II.(Spitzer, 1995)

Kinematic results of both groups, with group difference results and associated effect size are presented in Table 2. Group difference analysis showed significant and strong effect-size differences in peak and mean velocities, NVP and TTPP in all directions excluding TTPP in left rotation. Accuracy measures demonstrated significant group differences in both X and Y for flexion, in X for extension, and in Y for right and left rotations.

Figure 3 presents typical examples of patient and control velocity profiles. The motion plots shows that the patient moved more slowly throughout the trial (less mean velocity), and accelerated to a lower peak velocity than the control subject. In addition, the figure reflects the symmetry (TTPP) between the acceleration and the deceleration phases in the control velocity profile creating a bell shaped profile, unlike the patient's profile.

Insert Figure 3 here

Insert Table 2 here

Results of the regression analysis and ROC curves (Table 3) show that the measures which demonstrated a strong group difference, were also very sensitive and specific.

Insert Table 3 here

Excellent sensitivity was found for mean and peak velocity in all directions of motion (ranged from 91% to 100%). Good sensitivity was also found for TTPP (range 82%-85%) with the exclusion of left rotation. NVP showed good sensitivity in flexion and left rotation, and accuracy varied in its sensitivity, which was good only in left rotation (85%). Specificity was high for peak and mean velocity for all directions (>86%), and good (>68%) for smoothness and symmetry (NVP and TTPP) in flexion, extension, and right rotation.

Discussion

Results of this study reinforced and expanded the demonstration of kinematic impairments in neck motion control by patients with chronic neck pain compared to asymptomatic control individuals. These findings, are consistent with previous evidence (Sjölander et al. , 2006, Roijezonet al., 2010, Sarig Bahatet al., 2010, Tsang et al. , 2014), and also support the validity of the newer version of VR system used here as the presented results replicated our previous findings of significantly less mean and peak velocities in those with neck pain compared to control individuals (Sarig Bahatet al., 2010). The current study also demonstrated differences with respect to motion smoothness (NVP) and symmetry (TTPP).(Vikneet al., 2013, Kristjansson and Oddsdottir, 2010, Sarig Bahat et al. , 2014a)

In the current study however, difference in NVP was unexpectedly higher, rather than lower, in the control subjects and was in contrast to our previous research. It had been hypothesized that normal smooth motion would consist of only one velocity peak. (Sarig Bahatet al., 2010). There are a number of considerations to this finding. Direct comparison between the studies is difficult since the NVP is a factor representing the level of disturbance in the recorded signal and the tracking device and filtering used in the current study were different to the previous study. In addition, small changes (less than 2 SDs) in a low velocity profile would have not produced an NVP count, which may also explain the current results. Further, interpretation of measures of noise, such as this, can also be ambiguous. Higher NVP may be interpreted as ineffective control as we had hypothesized but it could be argued that increased complexity or noise of the signal (higher NVP) could be interpreted as a sign of a healthy vigilant system and thus it is possible that the asymptomatic control subjects, who overall moved much faster, demonstrated more confident motion allowing more pace changes while patients may have been more hesitant.(Borg and Laxåback, 2010) Thus further research in this area will be important to evaluate all of these possibilities.

In the current study we also explored the symmetry of the velocity profile (TTPP) and found that patients had less symmetry of cervical motion compared to control subjects. Whilst this is consistent with a previous study by Roijezon et al. (Roijezonet al., 2010), TTPP did not significantly differ between groups in our previous research (Sarig Bahatet al., 2010). This result could be due to the neck pain group in both (Roijezonet al., 2010) and the current study having greater neck pain, disability and fear of motion than in our previously studied sample (Sarig Bahatet al., 2010). Further research is needed to determine the possible factors associated with symmetry of neck motion (TTPP) such as neck pain intensity, disability, range and fear of motion.

Beyond the established velocity, smoothness and symmetry impairments in neck pain, new kinematic measures were also explored. In the current study neck movement accuracy was found to be impaired in the neck pain group by measuring the accumulated error between a moving target and the participant’s moving head following that target. Neck motion accuracy has been studied previously using other methodologies and found to be impaired in patients with neck pain (Kristjansson and Oddsdottir, 2010, Woodhouseet al., 2010a). Current findings are in agreement with these previous studies which seem to enhance the value of this measure in clinical assessment of patients with neck pain. Moreover, unlike previous research that has looked at accuracy in a voluntary, self-paced control task, our study investigated accuracy in an interactive dynamic functional motion task. This measure seems particularly functional for reading, which requires smooth head pursuit in the X axis, and any pursuit of the head over a moving target, such as in ball games i.e. tennis, basketball etc.

An important component of this study was the investigation of the sensitivity and specificity of the various kinematic measures. The regression analysis and ROC curves showed that the most sensitive parameters were peak and mean velocity with excellent results showing that these measures were impaired in the majority of patients. Further, specificity of neck movement velocity was very high as well, differentiating true controls from patients in more than 90% of the cases in rotations and flexion, and in 85% in extension. These findings are higher than the sensitivity and specificity we have previously reported for ROM which was 88% in 3/8 measures, and smaller than 80% in 5/8 cases (Sarig-Bahatet al., 2010). Röijezon et al. reported peak velocity had a sensitivity of 76% and a specificity of 78%, while lower values were found for ROM (sensitivity 64.4%, specificity 71.4%) (Roijezonet al., 2010). Although Röijezon et al.'s values are lower than the current study, the clinical value of velocity over ROM is supported by both studies. The difference in values may be explained by the different assessment methodology in the two studies. They collected fast movement in response to an instruction and an auditory beep, with no interaction or feedback, while we used the interactive VR platform with random appearance of targets and real-time feedback. Assessing self-initiated neck movement and not task-oriented movement may be less functional and may produce slower motion or more variable velocity, which limits comparability. Nevertheless, this suggests cervical motion velocity has a high clinical value and should be applied to the assessment of patients with chronic neck pain. In addition, current findings provide new evidence for the clinical value of NVP and TTPP, which should be further studied in various patients' populations.

An important contribution of this research is the optimal predictor values (i.e. cut offs) which could be applied to identify presence or absence of kinematic impairments in patients, and could direct management accordingly. For example, patients with mean velocity higher than 50 and 60 degrees per second in flexion-extension, and rotations respectively, probably do not need addressing this factor in management, and further assessment are needed to consolidate treatment strategy for them.

As neck pain etiology remains uncertain, the common approach is to direct management to the impairments identified. As such, impaired neck kinematics should be addressed clinically. In a recent pilot trial, we demonstrated the potential value of kinematic training using this system with positive results (Sarig-Bahat et al. , 2014). The results of this current study confirm the need for further research in this area and the establishment of appropriate classification criteria for kinematic assessment and treatment

Further the specific findings of this study might have some implications for directions for management. Since, dynamic neck motion control in daily life seems to commonly occur in response to surrounding stimuli which frequently stimulate rotation. An interesting insight lies in the difference in the results in flexion-extension versus rotation. Cervical rotations were faster than flexion and extension which has been shown before (Dvir et al. , 2006, Sarig-Bahatet al., 2014). Research also shows higher repeatability and sensitivity of horizontal measures relative to sagittal ones (Dall'Alba et al. , 2001, Lantz et al. , 2003, Dviret al., 2006, Sarig-Bahatet al., 2010) as well as greater ROM in the horizontal plane(Chen et al. , 1999, Sarig-Bahatet al., 2010). These findings may have functional significance for rehabilitation.

There were a few limitations to this study that should be considered in future research. Firstly, velocities produced here and in our previous study are very similar to Tsang et al.(Tsanget al., 2013), higher than Sjölander et al.(Sjölander et al., 2006), and lower than Roijezon et al (Roijezonet al., 2010). This variability can be explained by the different methodologies used to produce and track neck motion. However all studies are in agreement as to velocity differences between patients and controls.

Secondly the VR system facilitated motion in flexion, extension, RR, and LR directions; however, it was not programmed to elicit isolated lateral flexion, except when coupled with rotation. In order to elicit isolated lateral flexion, a separate task is needed. Moreover, the VR velocity module was assessed in sitting. This may be very relevant to working positions in office/computer workers, but other functional positions such as standing or walking should also be explored for their effect on neck kinematics.

Lastly, this group of patients included patients with both whiplash and idiopathic neck pain. There is some evidence to suggest cervical motion control does not differ between these two sub-groups, but ideally future research should enlarge the population to allow comparison of kinematic performance between whiplash-associated disorders and idiopathic neck pain. To further explore the differential diagnostic potential of these measures it will also be important to consider other populations where velocity of neck motion might be impaired, such as individuals with dizziness or vestibular disorders, or workers with high vestibular demands such as pilots and divers. Lastly, further research should investigate the relationships between subjective reports, psychological factors and movement behavior, and objective factors such as range of motion, sensorimotor control, strength, vestibular function, to better understand the factors that contribute to impaired kinematic performance.

Conclusion

This study supports previous evidence that patients with neck pain move their cervical spine more slowly, with reduced motion accuracy and symmetry when compared to asymptomatic control individuals. Regression results emphasized the high clinical value of neck motion velocity, with very high sensitivity and specificity, followed by motion smoothness and symmetry. These finding suggest cervical kinematics including motion velocity, symmetry, smoothness and accuracy should be evaluated clinically, and screened by the provided cut off values for identification of relevant impairments in those with neck pain. Such identification of presence or absence of kinematic impairments may direct treatment strategies and additional evaluation when needed.

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Table 2. Kinematic results by groups, with group difference analysis results and effect size.

Movement direction	Kinematic measure	Controls (N=22)		Patients (N=33)		Sig. (2-tailed)	95% Confidence limits		Cohen's d
		Mean	SD	Mean	SD		Lower	Upper	
Flexion	**Peak Velocity**	**166.82**	**69.6**	**50.34**	**20.2**	**0.00**	**90.79**	**142.17**	**2.59**
	Mean Velocity	**83.82**	**33.3**	**20.14**	**9.0**	**0.00**	**51.48**	**75.86**	**3.01**
	NVP	**2.79**	**1.1**	**1.24**	**0.8**	**0.00**	**1.04**	**2.06**	**1.64**
	TTPP	**52.73**	**18.4**	**24.84**	**10.3**	**0.00**	**20.12**	**35.67**	**1.94**
	Sway Yaw (SD)	0.49	0.2	0.54	0.2	0.29	-0.16	0.05	-0.30
	Sway Pitch (SD)	0.41	0.2	0.43	0.2	0.77	-0.12	0.09	-0.08
	Accuracy error X	**15.31**	**4.6**	**25.53**	**12.0**	**0.00**	**-15.61**	**-4.82**	**-1.23**
	Accuracy error Y	**44.51**	**11.6**	**70.83**	**28.7**	**0.00**	**-39.27**	**-13.36**	**-1.31**
Extension	**Peak Velocity**	**149.05**	**68.6**	**55.30**	**30.3**	**0.00**	**66.58**	**120.91**	**1.89**
	Mean Velocity	**76.89**	**33.1**	**29.08**	**17.1**	**0.00**	**34.17**	**61.46**	**1.90**
	NVP	**2.42**	**1.3**	**1.40**	**1.2**	**0.00**	**0.33**	**1.71**	**0.81**
	TTPP	**59.32**	**16.3**	**34.69**	**13.1**	**0.00**	**16.67**	**32.60**	**1.68**
	Sway Yaw (SD)	0.49	0.1	0.55	0.1	0.07	-0.14	0.01	-0.50
	Sway Pitch (SD)	0.41	0.1	0.44	0.2	0.52	-0.15	0.08	-0.19
	Accuracy error X	22.89	28.0	36.06	21.4	0.05	-26.56	0.22	-0.53
	Accuracy error Y	**34.12**	**8.3**	**59.76**	**24.3**	**0.00**	**-36.46**	**-14.81**	**-1.57**
Right Rotation	**Peak Velocity**	**220.93**	**89.2**	**66.64**	**31.1**	**0.00**	**120.54**	**188.03**	**2.56**
	Mean Velocity	**100.69**	**40.1**	**32.88**	**15.2**	**0.00**	**52.43**	**83.20**	**2.45**
	NVP	**3.50**	**1.3**	**1.99**	**1.2**	**0.00**	**0.83**	**2.19**	**1.21**
	TTPP	**43.42**	**17.4**	**29.07**	**12.3**	**0.00**	**6.33**	**22.37**	**0.97**
	Sway Yaw (SD)	0.48	0.2	0.55	0.2	0.15	-0.18	0.03	-0.40
	Sway Pitch (SD)	0.41	0.1	0.44	0.2	0.49	-0.12	0.06	-0.20
	Accuracy error X	**36.00**	**8.4**	**48.98**	**22.7**	**0.01**	**-23.16**	**-2.79**	**-0.83**
	Accuracy error Y	25.73	7.5	27.52	11.2	0.51	-7.26	3.68	-0.19
Left Rotation	**Peak Velocity**	**261.59**	**104.4**	**73.73**	**28.7**	**0.00**	**149.46**	**226.25**	**2.82**
	Mean Velocity	**100.60**	**33.1**	**34.91**	**14.0**	**0.00**	**52.63**	**78.75**	**2.78**
	NVP	**3.50**	**1.2**	**2.23**	**1.0**	**0.00**	**0.68**	**1.86**	**1.17**
	TTPP	52.07	24.0	44.51	23.4	0.25	-5.49	20.61	0.32
	Sway Yaw (SD)	**0.45**	**0.1**	**0.56**	**0.2**	**0.03**	**-0.20**	**-0.01**	**-0.63**
	Sway Pitch (SD)	0.47	0.1	0.43	0.2	0.38	-0.05	0.13	0.28
	Accuracy error X	**43.35**	**16.7**	**57.40**	**20.9**	**0.01**	**-24.73**	**-3.36**	**-0.75**
	Accuracy error Y	27.16	8.1	30.62	14.8	0.32	-10.41	3.50	-0.30

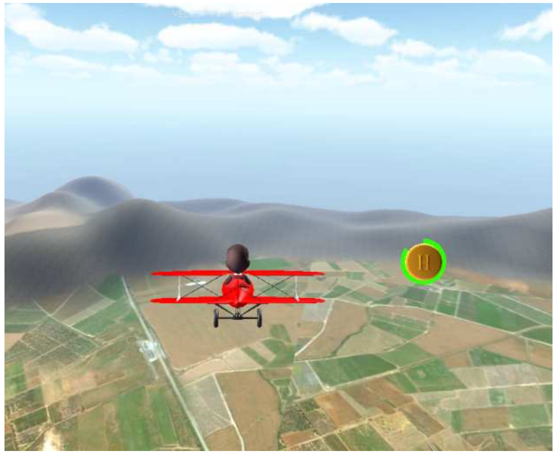
NVP- number of velocity peaks, representing movement smoothness; TTPP- time to peak velocity percentage, i.e. the acceleration/deceleration ratio representing level of symmetry of the velocity profile. Sway yaw/pitch SD- Standard deviation of head sway when stabilizing head on target before target appearance, for yaw and for pitch; Accuracy error X/Y- the accumulated error between head motion and target motion in the accuracy assessment module, in X and Y displacement.

Table 3. Regression and ROC curve results

Movement direction	Outcome measure	Model	Predictor	Optimal Predictor Value	Unit Odds	95% Confidence Limits		Sensitivity	95% Confidence Limits		specificity	95% Confidence Limits		Sensitivity-(1-specificity)	Area under curve	95% Confidence Limits	
		Sig.	Sig.		Ratio	Lower	Upper		Lower	Upper		Lower	Upper			Lower	Upper
Flexion	**Peak Velocity**	<.0001 *	0.0021 *	88.22	0.91	0.85	0.97	0.97	0.84	1.00	0.95	0.77	1.00	0.92	0.99	0.96	1.00
	Mean Velocity	<.0001 *	0.00	43.97	0.86	0.78	0.94	0.97	0.84	1.00	0.95	0.77	1.00	0.92	0.97	0.92	1.00
	NVP	<.0001 *	0.0001 *	0.02	0.20	0.09	0.45	0.88	0.72	0.97	0.73	0.50	0.89	0.61	0.88	0.79	0.97
	TTPP	<.0001 *	<.0001 *	29.73	0.89	0.84	0.94	0.82	0.65	0.93	0.91	0.71	0.99	0.73	0.90	0.79	1.00
	Accuracy error X	<.0001 *	0.0032 *	18.32	1.24	1.08	1.44	0.67	0.48	0.82	0.86	0.65	0.97	0.53	0.82	0.71	0.93
	Accuracy error Y	<.0001 *	0.0007 *	54.47	1.11	1.05	1.18	0.76	0.58	0.89	0.82	0.60	0.95	0.58	0.84	0.73	0.94
Extension	**Peak Velocity**	<.0001 *	0.0002 *	89.67	0.95	0.93	0.98	0.94	0.80	0.99	0.86	0.65	0.97	0.80	0.94	0.87	1.00
	Mean Velocity	<.0001 *	0.0001 *	49.80	0.93	0.89	0.96	0.94	0.80	0.99	0.86	0.65	0.97	0.80	0.91	0.81	1.00
	NVP	0.0037 *	0.0172 *	0.01	0.49	0.27	0.88	0.55	0.36	0.72	1.00	0.85	1.00	0.55	0.81	0.69	0.92
	TTPP	<.0001 *	<.0001 *	43.36	0.90	0.85	0.95	0.85	0.68	0.95	0.86	0.65	0.97	0.71	0.88	0.77	0.98
	Accuracy error X	0.0263 *	0.07	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.82	0.69	0.94
	Accuracy error Y	<.0001 *	0.0002 *	49.95	1.12	1.06	1.19	0.73	0.54	0.87	0.95	0.77	1.00	0.68	0.87	0.78	0.96
Right Rotation	**Peak Velocity**	<.0001 *	0.0008 *	106.36	0.95	0.93	0.98	0.91	0.76	0.98	0.95	0.77	1.00	0.86	0.97	0.94	1.00
	Mean Velocity	<.0001 *	0.0003 *	53.66	0.91	0.87	0.96	0.94	0.80	0.99	0.91	0.71	0.99	0.85	0.95	0.88	1.00
	NVP	<.0001 *	0.0010 *	2.33	0.36	0.20	0.66	0.73	0.54	0.87	0.82	0.60	0.95	0.55	0.82	0.74	0.96
	TTPP	0.0007 *	0.0034 *	36.49	0.93	0.89	0.98	0.82	0.65	0.93	0.68	0.45	0.86	0.50	0.75	0.60	0.88
	Accuracy error X	0.0049 *	0.0255 *	51.56	1.06	1.01	1.12	0.50	0.37	0.63	0.86	0.73	0.95	0.36	0.69	0.55	0.83
	Accuracy error Y	0.50	0.51	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Left Rotation	**Peak Velocity**	<.0001 *	0.0022 *	126.81	0.94	0.91	0.98	0.94	0.80	0.99	0.95	0.76	1.00	0.89	0.98	0.96	1.00
	Mean Velocity	<.0001 *	0.0021 *	61.00	0.88	0.81	0.95	1.00	0.89	1.00	0.90	0.70	0.99	0.90	0.96	0.89	1.00
	NVP	<.0001 *	0.0016 *	2.67	0.31	0.15	0.64	0.85	0.68	0.95	0.68	0.45	0.86	0.53	0.83	0.72	0.94
	TTPP	0.24	0.25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Accuracy error X	0.0073 *	0.0181 *	42.48	1.04	1.01	1.08	0.82	0.65	0.93	0.59	0.36	0.79	0.41	0.71	0.57	0.85
	Accuracy error Y	0.30	0.32	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

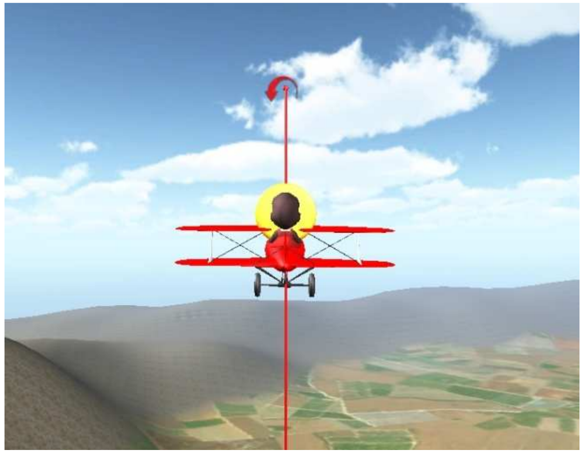
NVP- number of velocity peaks, representing movement smoothness; TTPP- time to peak velocity percentage, i.e. the acceleration/deceleration ratio representing level of symmetry of the velocity profile. Sway yaw/pitch SD- Standard deviation of head sway when stabilizing head on target before target appearance, for yaw and for pitch; Accuracy error X/Y- the accumulated error between head motion and target motion in the accuracy assessment module, in X and Y displacement.

Figure 1. The velocity module in the virtual reality assessment



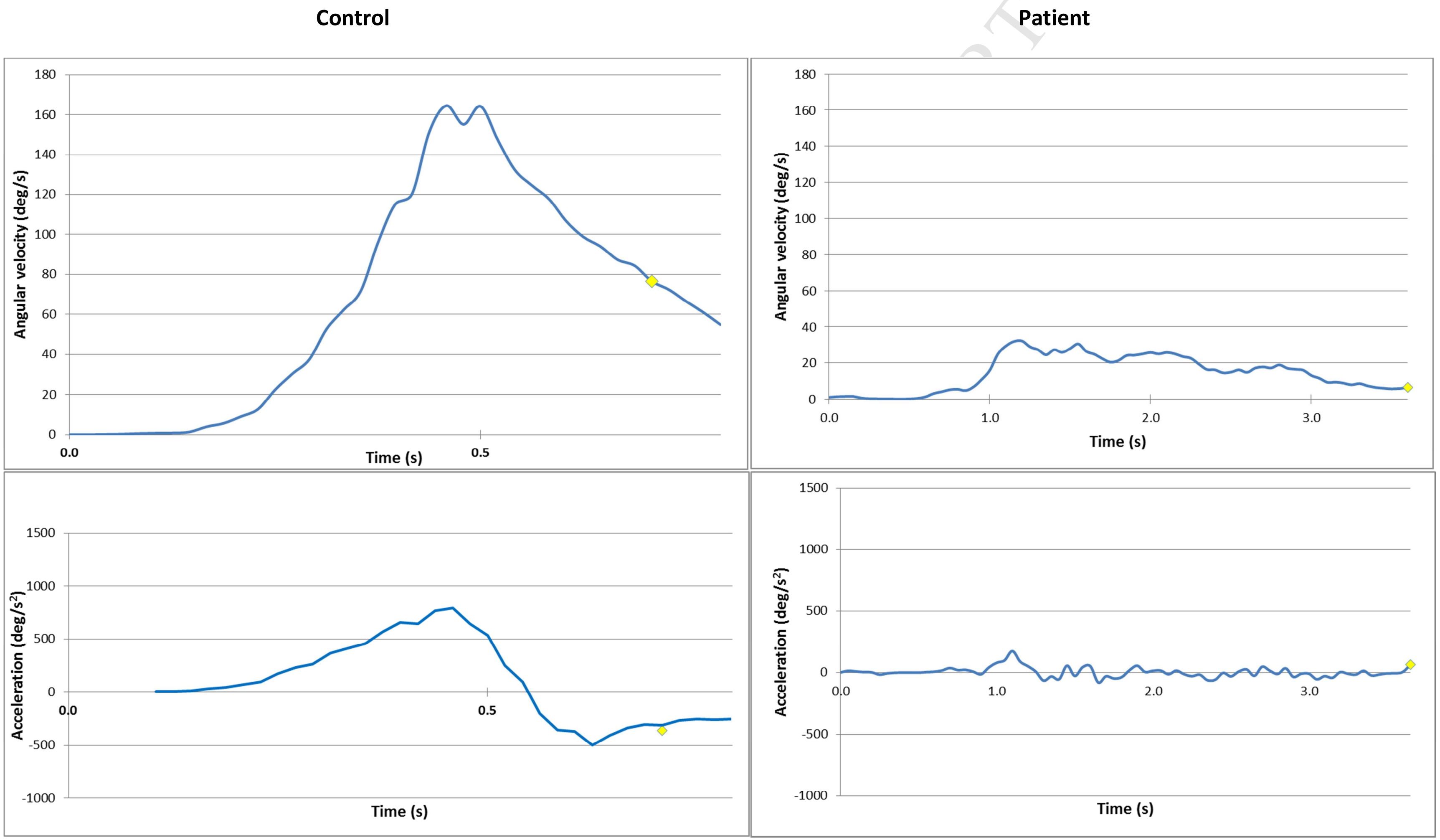
The velocity module is designed to randomly display a total of 16 yellow ball targets, in four different directions of flexion/extension and rotation. At the beginning of each trial, the participant has to activate the game by positioning the pilot's head in the center of a red ring, which is the recorded mid-position for three seconds. Once this is achieved, a yellow target appears in a random direction, and the participant is required to move the head in that direction within seven seconds before the target disappears. Target's life time is visualized using a green circle around the target that diminishes gradually and functions as a timer. This feature aims to motivate the participant to move quickly towards the target before it disappears.

Figure 2. The accuracy module in the virtual reality assessment



In the accuracy module a moving yellow target is presented on a vertical or horizontal line, at a constant velocity of 10 °/sec. The participant is required to maintain the pilot's head position on the moving target as closely as possible by tracing the vertical/horizontal line. The order of the movement directions of flexion/ extension/ right rotation/ left rotation is randomized.

Figure 3: Typical kinematic profiles in a control individual and a patient performing the virtual velocity task in a flexion-directed neck movement



The control's profile demonstrates a faster and smoother movement (Vpeak=164.5, Vmean=93.4, NVP=2), and a more symmetrical acceleration deceleration ratio (TTPP=50.6), compared to the patient (Vpeak=32.2, Vmean=14.8, NVP=4, TTPP=31.6). Targets were positioned at 40 degrees range of motion for all participants.

=Target hit

Interactive cervical motion kinematics: sensitivity, specificity and clinically significant values for identifying kinematic impairments in patients with chronic neck pain.

Highlights

- Patients with neck pain demonstrated impaired motion velocity, accuracy and symmetry.
- Cervical motion velocity was found highly sensitive and specific.
- Neck kinematics should be evaluated clinically.
- The provided cut off values can be used for identification of relevant impairments.
- Such identification of kinematic impairments may direct treatment strategies.